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F. S. Porter, G. V. Brown, K. R. Boyce, R. L. Kelley, C. A. Kilbourne, P. Beiersdorfer, H. Chen, S. Terracol, S. M. Kahn, A. E. Szymkowiak

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Frederick Scott Porter, Greg V. Brown, Kevin R. Boyce, Richard L. Kelley, and Caroline A. Kilbourne

NASA/GSFC, Greenbelt, MD

Peter Beiersdorfer, Hui Chen, and Stephane Terracol

Lawrence Livermore National Laboratory, Livermore, CA

Steven M. Kahn

Stanford University, Stanford, CA

Andrew E. Szymkowiak

Yale University, New Haven, CT

The X-ray Spectrometer (XRS) instrument is a revolutionary non-dispersive spectrometer that will form the basis for the Astro-E2 observatory to be launched in 2005. We have recently installed a flight spare XRS microcalorimeter spectrometer at the EBIT-I and SuperEBIT facility at LLNL replacing the XRS from the earlier Astro-E mission and providing twice the resolving power. The XRS microcalorimeter is an x-ray detector that senses the heat deposited by the incident photon. It achieves a high energy resolution by operating at 0.06K and by carefully engineering the heat capacity and thermal conductance. The XRS/EBIT instrument has 32 pixels in a square geometry and achieves an energy resolution of 6 eV at 6 keV, with a bandpass from 0.1 to 12 keV (or more at higher operating temperature). The instrument allows detailed studies

of the x-ray line emission of laboratory plasmas. The XRS/EBIT also provides an extensive calibration "library" for the Astro-E2 observatory.

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Introduction

The XRS/EBIT microcalorimeter system is based on the XRS microcalorimeter spectrometer that will be part of the Astro-E2 orbiting observatory that is a collaboration between NASA and JAXA/ISAS in Japan.[1] The XRS/EBIT spectrometer was built to complement the dispersive spectrometers at the Electron Beam Ion Trap (EBIT I and SuperEBIT) facility at the Lawrence Livermore National Laboratory. The LLNL/EBIT facility provides a unique ground based laboratory for reproducing astrophysical plasmas, controlling in detail, the ionization state, composition, and electron beam energy[2].

The XRS/EBIT contains a 32 element detector array (shown in Figure 1) consisting of 28 detector elements with a 0.1-12 keV bandpass and a resolving power of 1000 at 6 keV and 4 detector elements with a 0.5-100 keV bandpass and a resolving power of ~1000 at 60 keV. The system is completely non-dispersive, and has a photon timing resolution of 10 μs. We have been operating the XRS/EBIT detector at the EBIT facility since 2000[3] and in October 2003 we substantially upgraded its performance, approximately doubling the resolving power at 6 keV.

A microcalorimeter x-ray detector overcomes many of the limits of other spectroscopic techniques both for laboratory plasma diagnostics and for x-ray astronomy. The non-dispersive nature and much higher resolving power of the microcalorimeter makes it an excellent complement to imaging CCD cameras for spectroscopy in x-ray astronomy. For plasma

diagnostics, the broad bandpass, efficiency, and lack of an aperture stop, makes the microcalorimeter an excellent complement to the much higher resolving power dispersive spectrometers.

A microcalorimeter x-ray detector operates on a very simple principle: to detect the heat deposited by an x-ray interacting with an absorber material using a very sensitive thermometer.[4,5] In practice this means constructing an absorber material with a high quantum efficiency that thermalizes the energy deposited by the induced photo-electron, Auger electron(s) and their thermalization cascade. In our microcalorimeter detectors, the absorber is bonded to a monolithic thermometer and the composite is weakly coupled to a thermal sink in order to reset the detector after each x-ray interaction. The heat capacity and thermal link to the heat sink control the time constant of the detector and contribute to the dominant phonon noise that limits the resolving power of the detectors. The final tunable parameter is the sensitivity of the thermometer. The XRS/EBIT currently uses a Mott hopping conductivity thermometer formed by doping the silicon substrate of the detector chip. The detector array can thus be monolithically constructed using standard MEMS techniques with hand assembly limited to the attachment of the HgTe x-ray absorbers.

The XRS/EBIT Spectrometer

The current XRS/EBIT spectrometer consists of 36 detector elements, each 640 μm square in a 6x6 square geometry with 32 read out channels as shown in figure 1.[6] An x-ray absorber is attached to each detector element: 34 elements with low energy 8 μm thick HgTe absorbers and 4 with 30 μm thick Bi absorbers. The detectors are cooled to 0.06 K using an LN_2/LHe/Adiabatic Demagnetization Refrigerator (ADR) cryostat custom built at NASA/GSFC.

The detectors are read out with a cold JFET source follower at 130K located 2 cm from the detector. The leads to the JFET are 20 μm in diameter and tensioned to minimize the heat load to the detector and microphonic pickup in the readout. The analog and digital data acquisition electronics are laboratory copies of the Astro-E2/XRS spaceflight electronics and consist of commandable JFET control, and gain stages, followed by dedicated ADCs and a dedicated DSP per channel. We use an "optimal" matched digital filter for processing each x-ray event into an incident energy. This as well as time-tagging, event grading, and telemetry are all handled in real time by the stand alone instrument electronics.

The instrumental response has been verified to be Gaussian to at least 2.5 orders of magnitude down the wings for a monochromatic x-ray line making the instrumental response function easy to model. This was verified using a double crystal monochrometer during the recent Astro-E2/XRS ground calibration. An example instrumental response is shown in Figure 2 for incident Copper K_α x-rays that were energy selected using a double crystal monochrometer. The energy resolution is 6-7 eV across the array. We believe the small deviations on the wings are due to non-stationary environmental noise in the building. The continuum at lower energies is a ~5% spectral redistribution due to photo-electron escape in the absorber.[7] By lowering the temperature from 60 mK to 51 mK we can substantially improve the energy resolution, basically because the limiting phonon noise of the system scales as $\sqrt{C}$, the heat capacity, which in turn scales as T^3.[5] This is shown for a single channel at 3.3 keV in Figure 3 giving approximately a 4 eV resolution across the array.

The XRS/EBIT instrument has 4 infrared blocking filters in the aperture to limit the bolometric response of the detectors and to minimize the radiative load on the cryogen tanks and the adiabatic demagnetization refrigerator. The filters are ~800 Å of aluminum on 1000 Å of

polyimide effectively reducing the radiative load on the detectors below our measurable limit of 1×10^{-16} W/pixel. The transmission function of the filters is essentially unity above 2 keV but the interpretation of relative line intensities requires a detailed calibration of the filter transmission at low energies. Careful attention must be given to the region just above the oxygen edge where the transmission is reduced by 90%. In addition both the Aluminum and Oxygen edges contain extended fine structure. We thus carefully measure the transmission function of each filter using a variable spaced grating spectrometer.[8] A final thin film filter isolates the dewar vacuum from the ultra-high vacuum of the EBIT to prevent gas contamination of the ion trap ($< 10^{-10}$ Torr).

The XRS/EBIT has been operating at the EBIT facility at LLNL for three years as a production system. The recent upgrades improved the resolution by a factor of two at 6 keV from 12 eV FWHM to 6 eV. Figure 4 shows an XRS/EBIT spectrum of Ni XXVII and Ni XXVIII produced in the EBIT-I facility at 16 keV electron beam energy. The XRS/EBIT clearly resolves the He-like triplet and the Ly_α complex. The XRS/EBIT has been used to measure line ratios, cross sections, charge exchange, and the ionization evolution of astrophysically interesting plasmas and will continue to be an important tool at the EBIT-I facility at LLNL.[9,10,11] In addition, the experience gained with the XRS/EBIT as a production instrument is invaluable experience for operating the Astro-E2/XRS in space when it is launched in February 2005 as well as providing an extensive calibration library for the observatory.

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Figure Captions.

Figure 1. The 36 pixel microcalorimeter array (center) within the Kevlar fiber suspended detector module. The four gray corner pixels are the high energy Bi x-ray absorbers The pixel size is 640 μm square.

Figure 2. The instrumental response to monochromatic x-rays energy selected from Cu K_α by a double crystal monochrometer. The instrument response is exceptionally gaussian with a resolution of 6-7 eV FWHM.

Figure 3. A spectrum of the emission from a ^{41}Ca source with the detector operating at 51 mK showing the improved energy resolution at lower operating temperatures. The solid line is the fit of the data to the dashed emission line model to derive the instrumental response.

Figure 4. A spectrum of helium-like and hydrogen like Nickel with a 16 keV electron beam energy in the EBIT-I at LLNL using the XRS/EBIT microcalorimeter spectrometer. The w,x,y, and z lines are the resonance, intercombination, and forbidden transitions from helium-like Ni XVII and the $Ly_{\alpha 1}$ and $Ly_{\alpha 2}$ are hydrogen-like Ni XVIII.
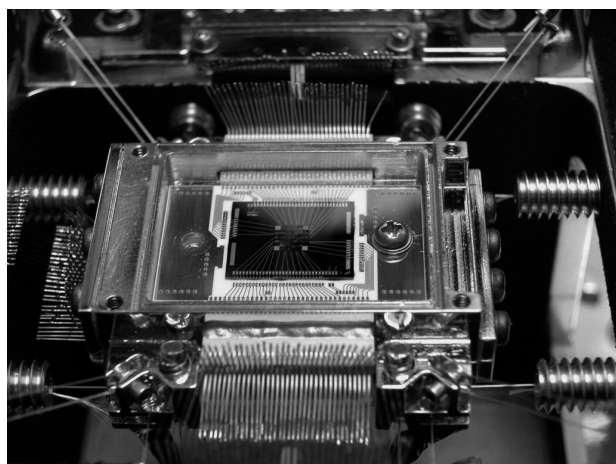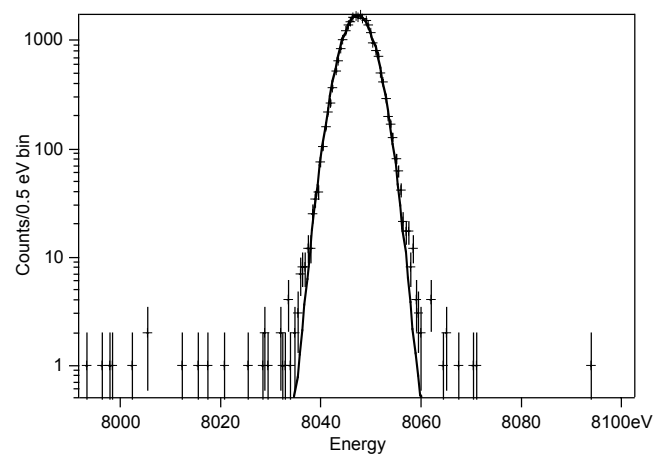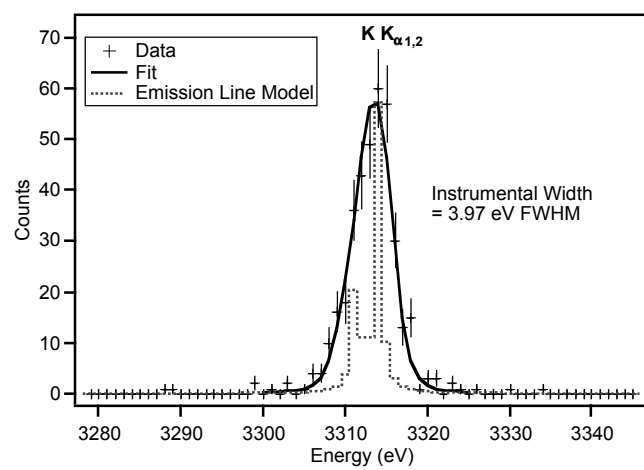
Figure 1.

Figure 2.

Figure 3.

Figure 4.